Non-destructive determination of single crystal elastic constants in AM alloys using Resonant Ultrasound Spectroscopy

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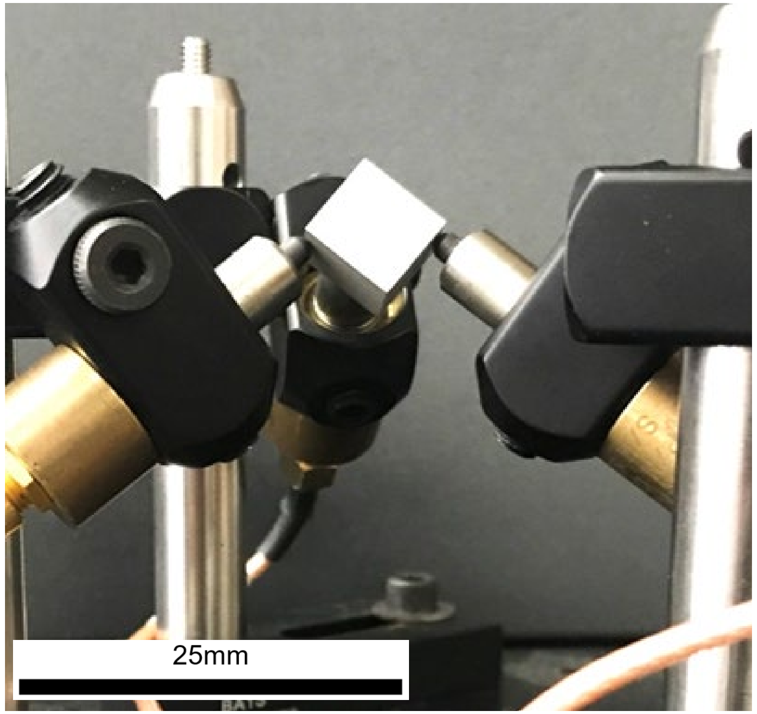
NASA SPACE TECHNOLOGY RESEARCH FELLOWSHIP

DOD VANNEVAR BUSH FELLOWSHIP

UC SANTA BARBARA MATERIALS

Goal: Infer single crystal elastic properties from NDE

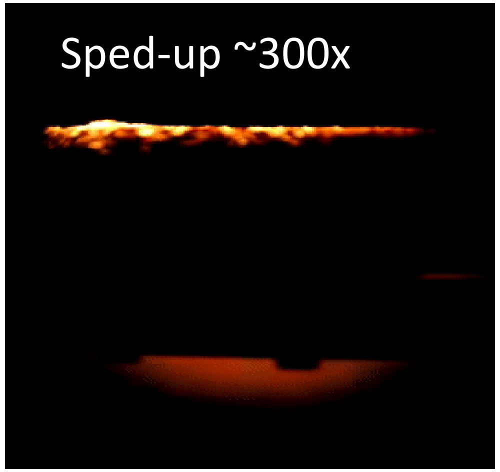
Resonant Ultrasound Spectroscopy (RUS)



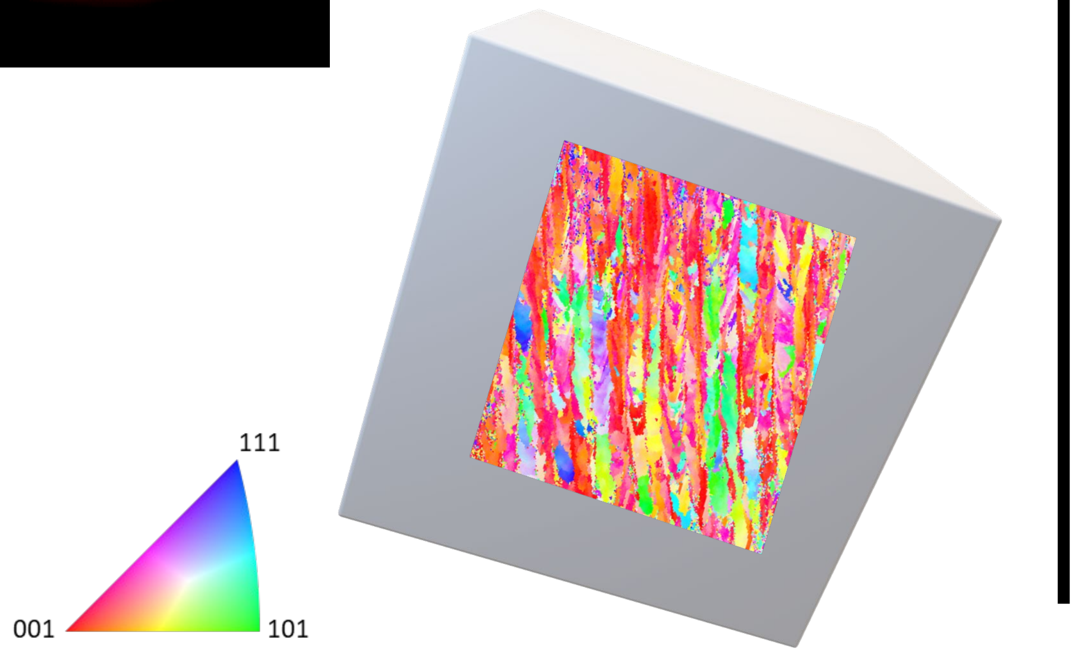
$$f_r = \left\{ \begin{bmatrix} 152.6 \\ . \\ . \\ . \\ . \\ 407.7 \end{bmatrix} \right\}$$

(kHz)

Textured AM sample



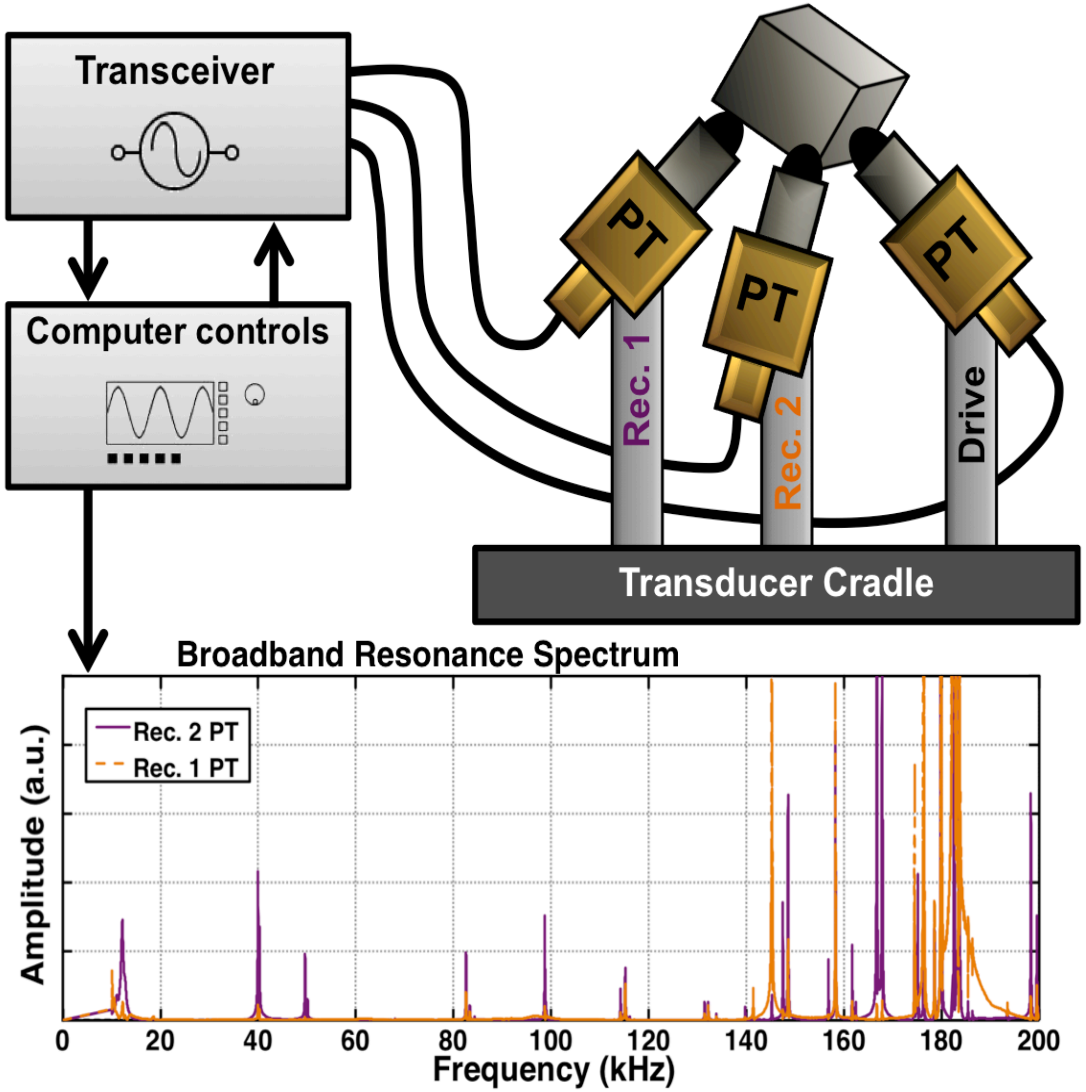
$$\begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix}$$



Outline

1. RUS computations to determine single crystal elastic constants
    - Sequential Monte Carlo
2. Additively manufactured Cobalt-Nickel base superalloy (SB-CoNi-10C)
    - Validating EBSD and neutron diffraction measurements
3. Single crystal elastic constants from RUS

Resonance ultrasound spectroscopy interrogates bulk elasticity in minutes

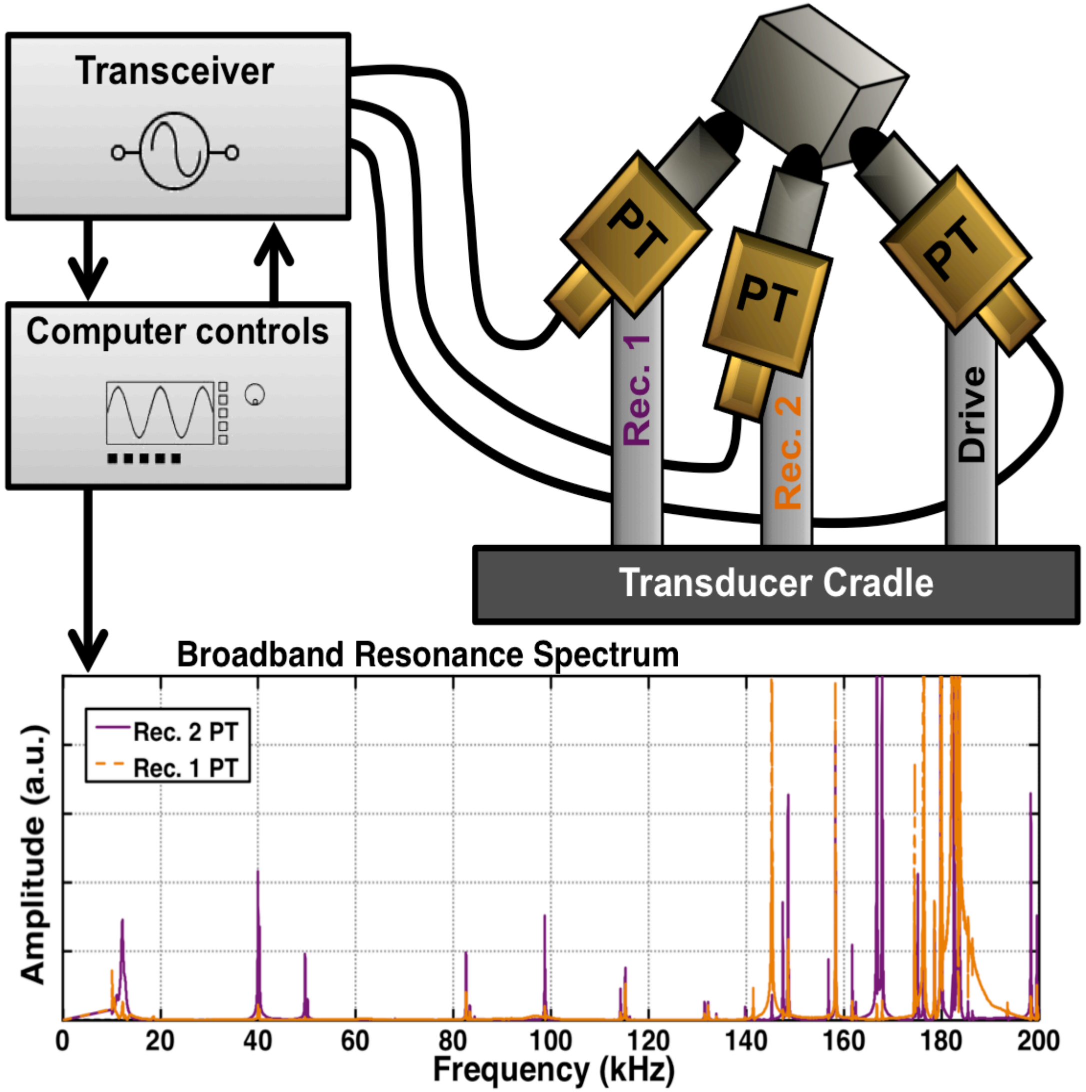


RUS depends on:

- Elastic Constants
- Shape, Density
- Microstructure (textured, equiaxed, single crystal)

$$\text{velocity}(v) = \sqrt{\frac{\text{elastic modulus}}{\text{density}}}$$

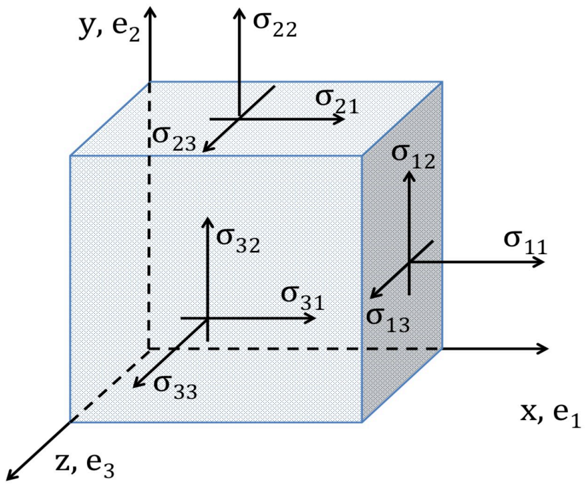
Resonance ultrasound spectroscopy interrogates bulk elasticity in minutes



stiffness tensor

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$$

stress tensor strain tensor

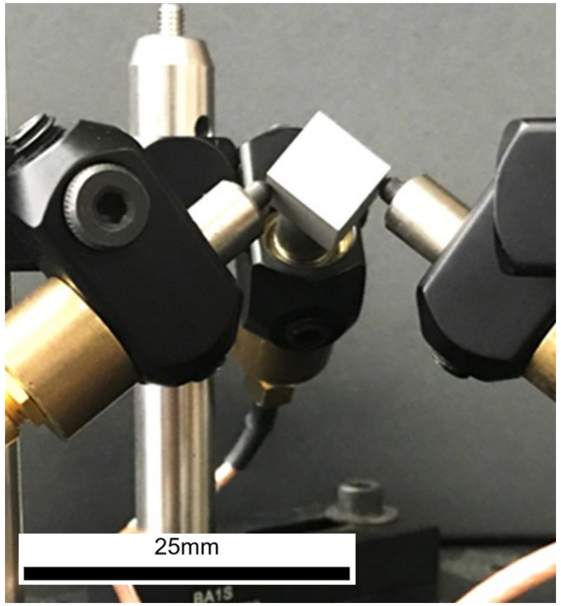


6 x 6 Voigt stiffness matrix representation

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \sigma_4\\ \sigma_5\\ \sigma_6\end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16}\\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26}\\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36}\\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46}\\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56}\\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \varepsilon_4\\ \varepsilon_5\\ \varepsilon_6\end{bmatrix}$$

Inverse problem compares experimental and calculated frequencies

Resonant Ultrasound Spectroscopy (RUS)



$$\left\{\begin{bmatrix} f_1^{meas} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ f_n^{meas} \end{bmatrix}\right\}$$

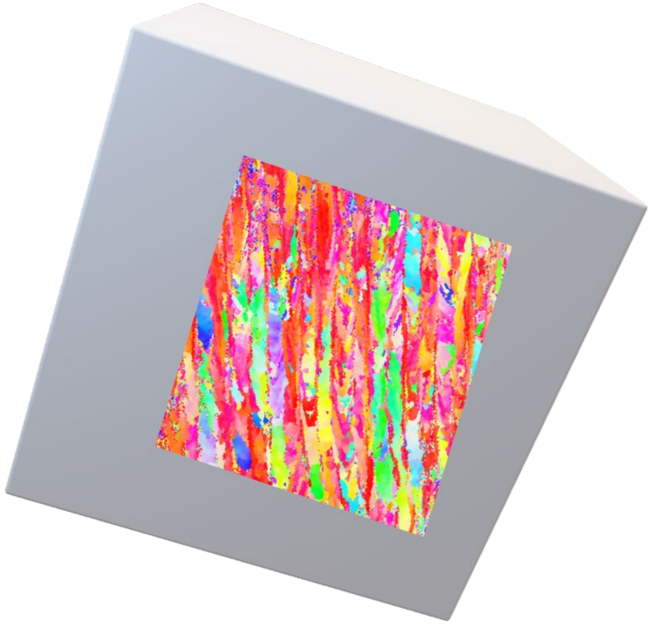
$$\left\{\begin{bmatrix} f_1^{calc} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ f_n^{calc} \end{bmatrix}\right\}$$

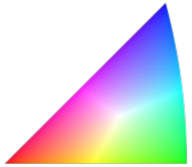
Resonance frequency calculation

Inverse problem

Aggregate Elastic Constants

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ - & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ - & - & C_{33} & C_{34} & C_{35} & C_{36} \\ - & - & - & C_{44} & C_{45} & C_{46} \\ - & sym. & - & - & C_{55} & C_{56} \\ - & - & - & - & - & C_{66} \end{bmatrix}$$



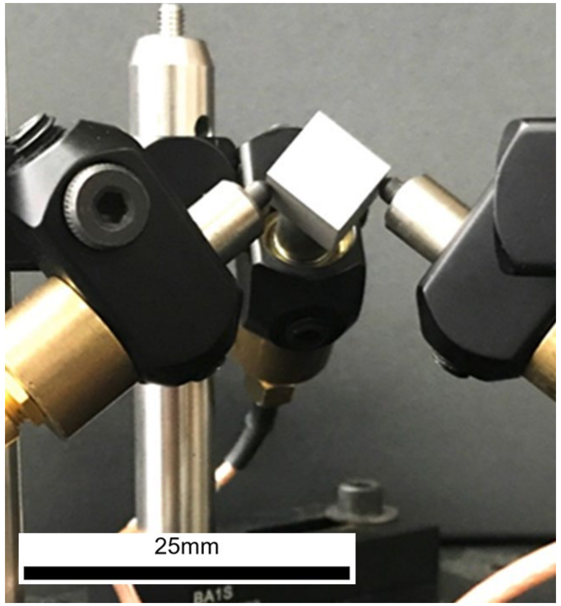


Rossin, J. et al (2021). Acta Mater, 117287.

EBSD NOT TO SCALE

Aggregate elasticity determined by single crystal elastic constants and texture

Resonant Ultrasound Spectroscopy (RUS)

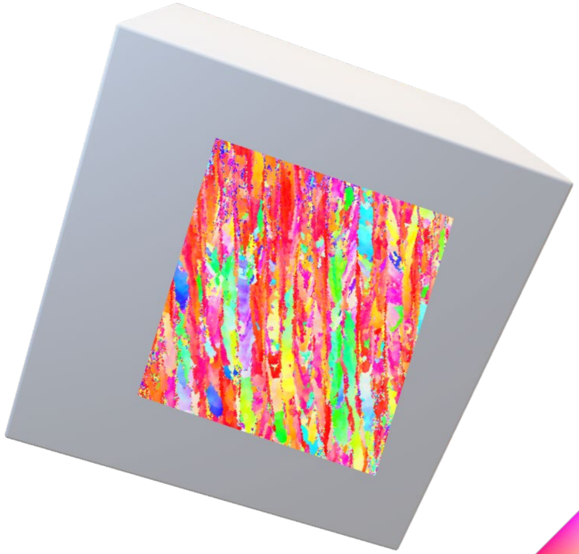


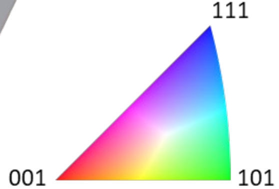
Forward model

Inverse problem

Aggregate Elastic Constants

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ - & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ - & - & C_{33} & C_{34} & C_{35} & C_{36} \\ - & - & - & C_{44} & C_{45} & C_{46} \\ - & sym. & - & - & C_{55} & C_{56} \\ - & - & - & - & - & C_{66} \end{bmatrix}$$





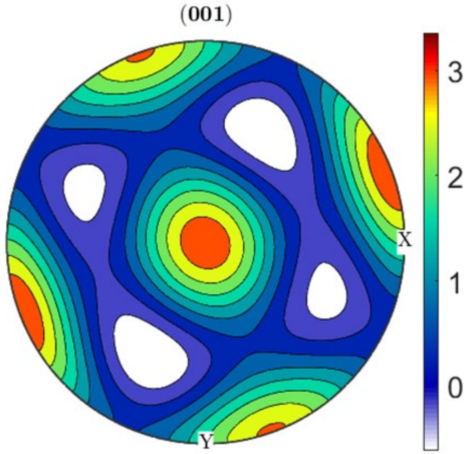
Bounded elastic estimate

Inverse problem

Single Crystal Elastic Constants

$$\begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix}$$

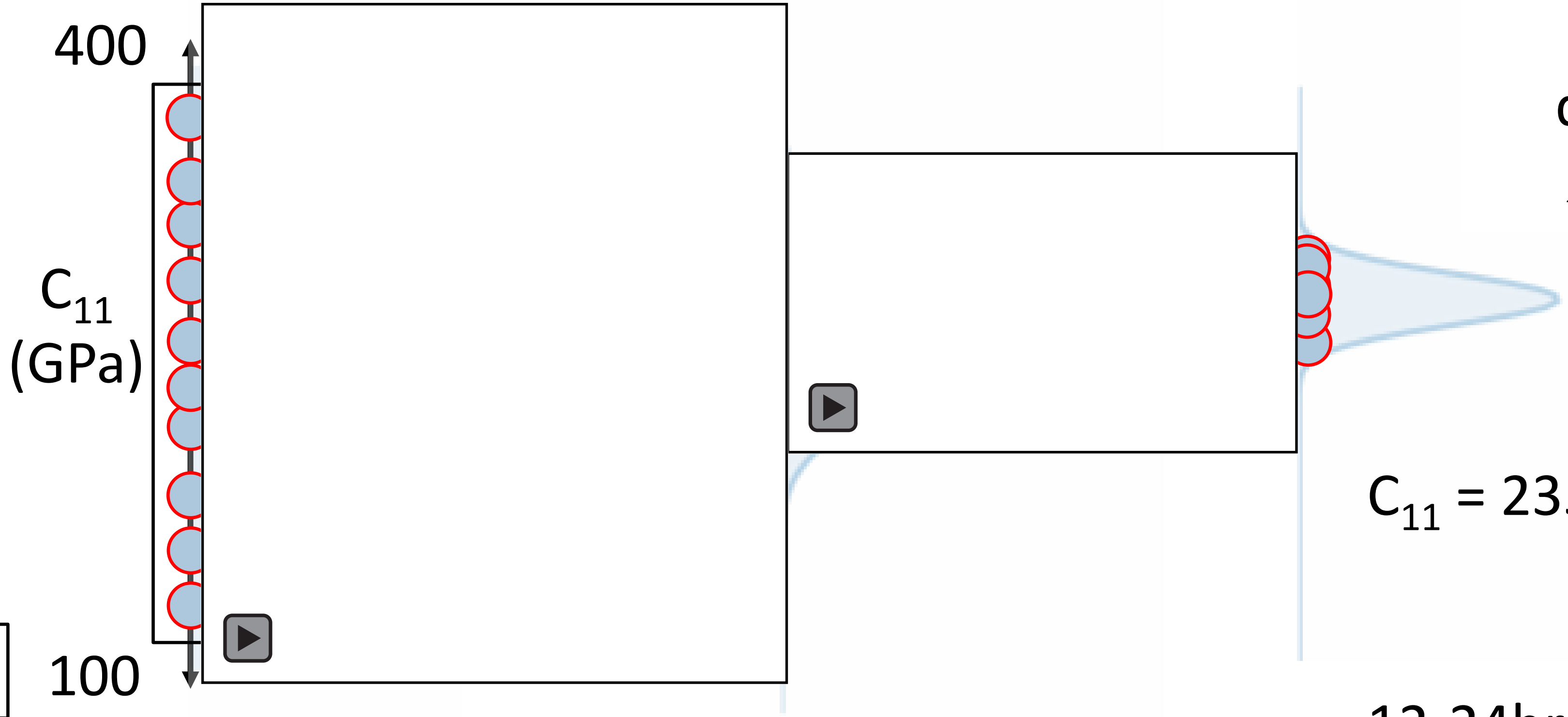
Known: Texture



Sequential Monte Carlo

Time

$$P(C_{sc}|f_r) = \frac{P(f_r|C_{sc})^t P(C_{SC})}{P(f_r)}$$



Posterior distribution $P(C^{SC}|f_r)$

C_{11} = 235.7 ± 2.4 GPa

12-24hrs on 10 CPU cores

$\boxed{C_{11} = 250 \pm 150 \text{ GPa}}$
C_{12} = 250 ± 150 GPa
C_{44} = 125 ± 75 GPa

$P(C_{11})$= Uniform(0,500 GPa)
$P(C_{12})$= Uniform(0,500 GPa)
$P(C_{44})$= Uniform(0,250 GPa)

$$\begin{bmatrix} \boxed{C_{11}} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix}$$

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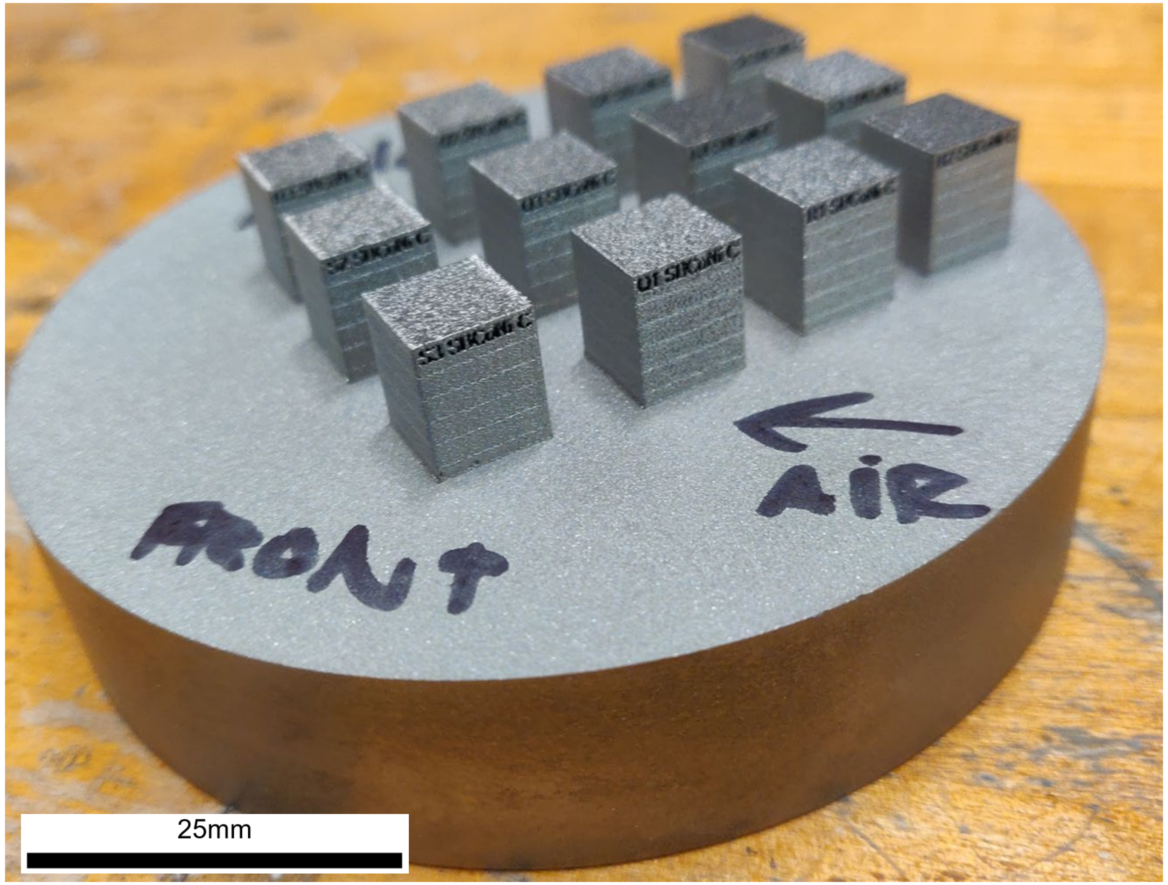
Cobalt-nickel base superalloy SB-CoNi-10C

	Co	Ni	Al	W	Ta	Cr	C	B	Y	Hf
wt%	Bal.	35.93	5.98	3.06	10.40	5.24	0.069	0.013	0.006	0.057



Specimen ID	Power (W)	Scan Speed (m/s)	Hatch Spacing (um)
R2	152	1.122	80
R4	130	0.833	80

10x10x13mm

Stress-relief heat treatment at 1100^{o}C 2hr

Grown Single Crystal (Bridgeman)

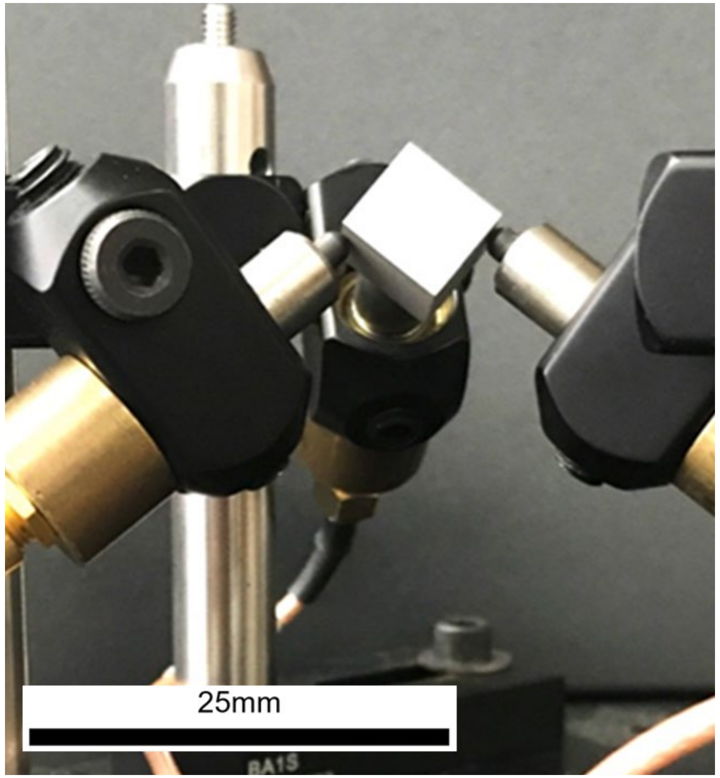
C_{11} = 236.4 ± 1.0 GPa

C_{12} = 150.8 ± 0.8 GPa

C_{44} = 134.1 ± 0.1 GPa

Quantifying single crystal constants dependent on texture data

Resonant Ultrasound Spectroscopy (RUS)



$$\left\{\begin{bmatrix} f_1^{meas} \\ . \\ . \\ . \\ . \\ f_n^{meas} \end{bmatrix}\right\}$$

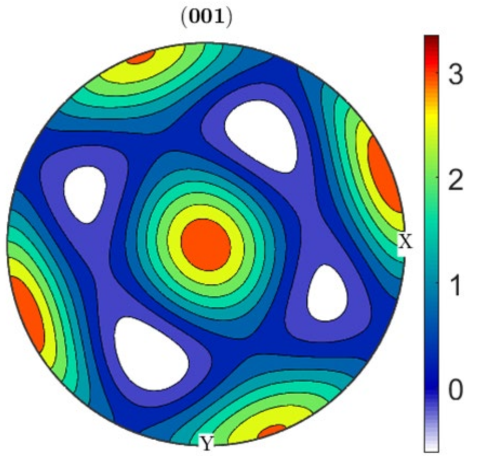
Resonance frequency calculation

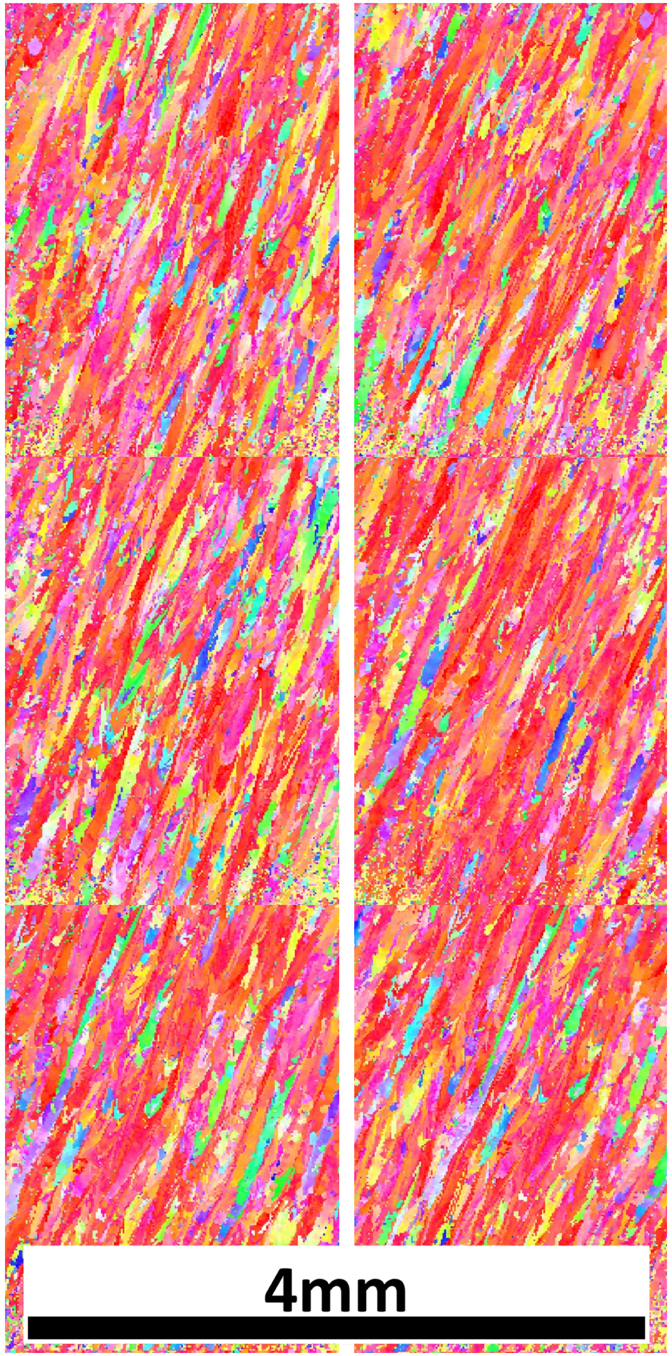
Inverse problem

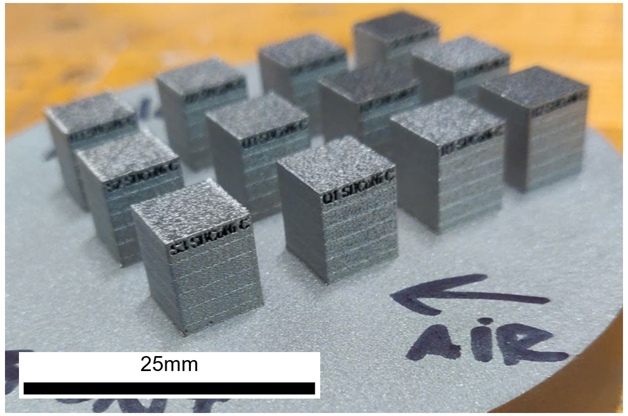
Single Crystal Elastic Constants

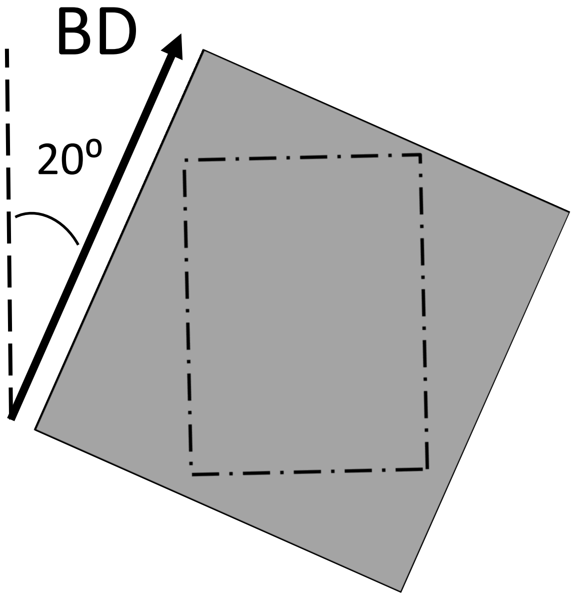
$$\begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix}$$

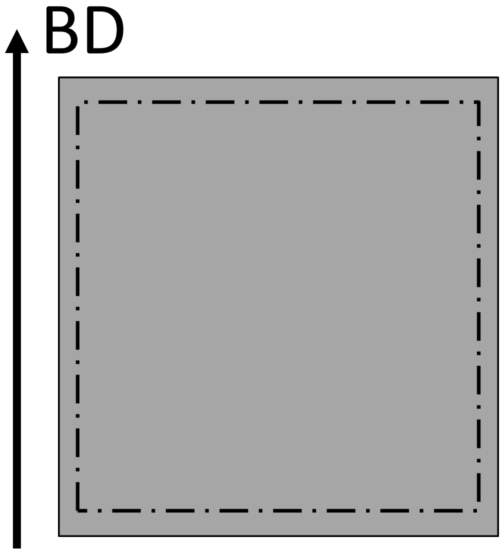
Known: Texture

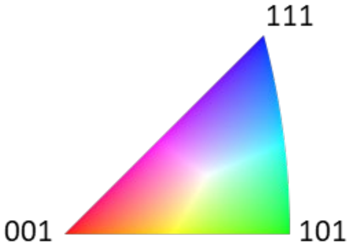


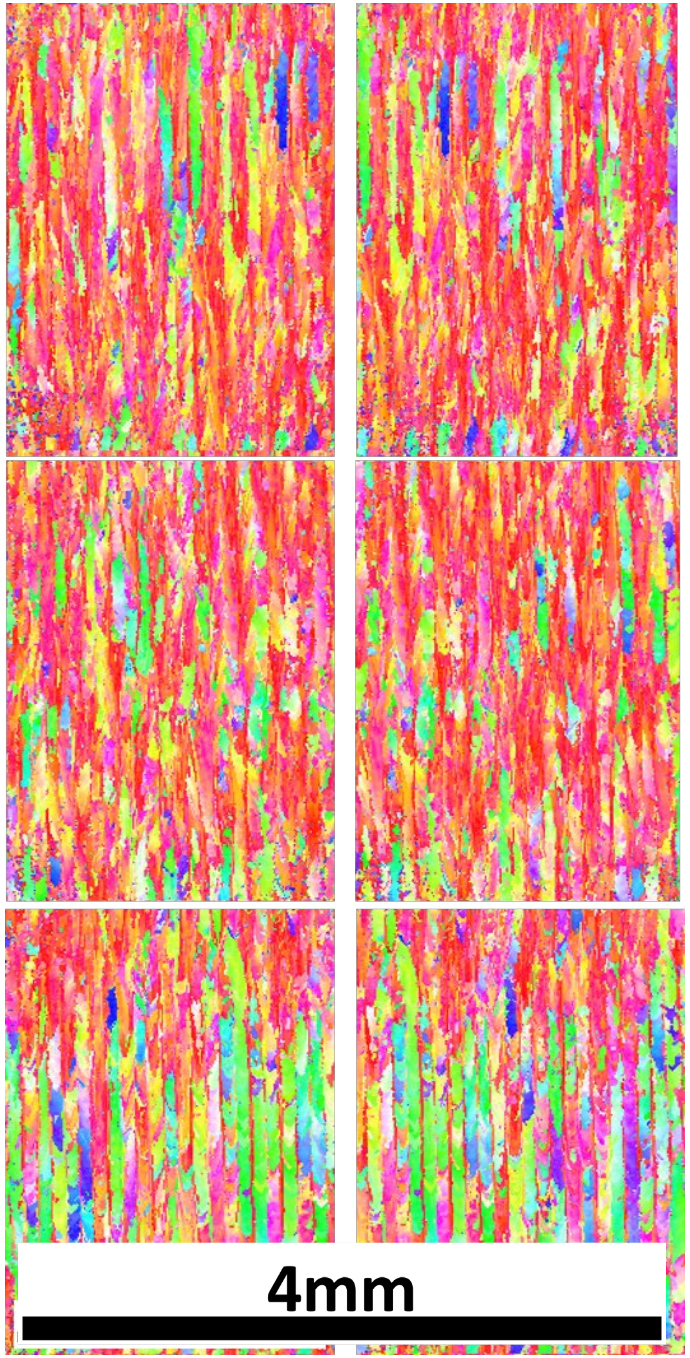

4mm


25mm
AIR

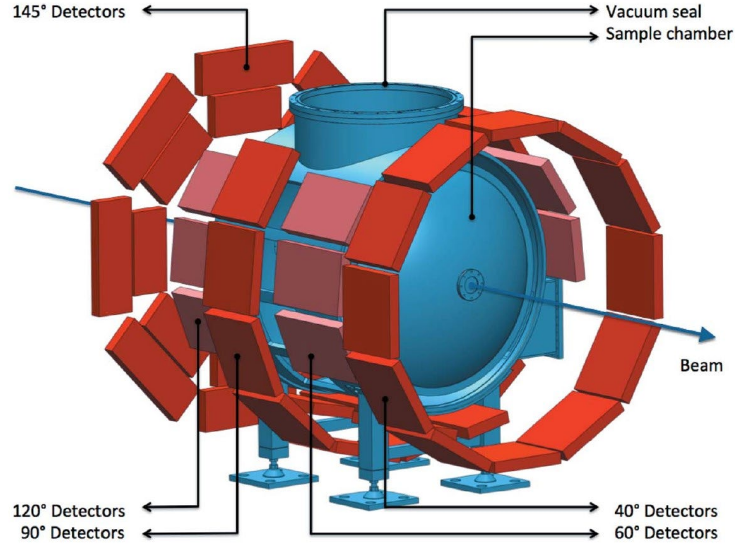

BD
20°

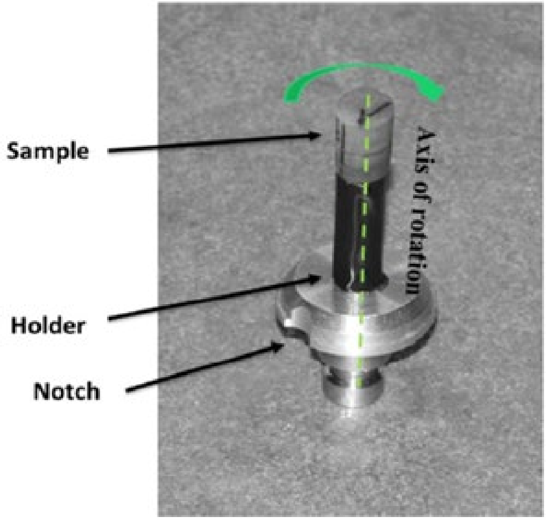

BD

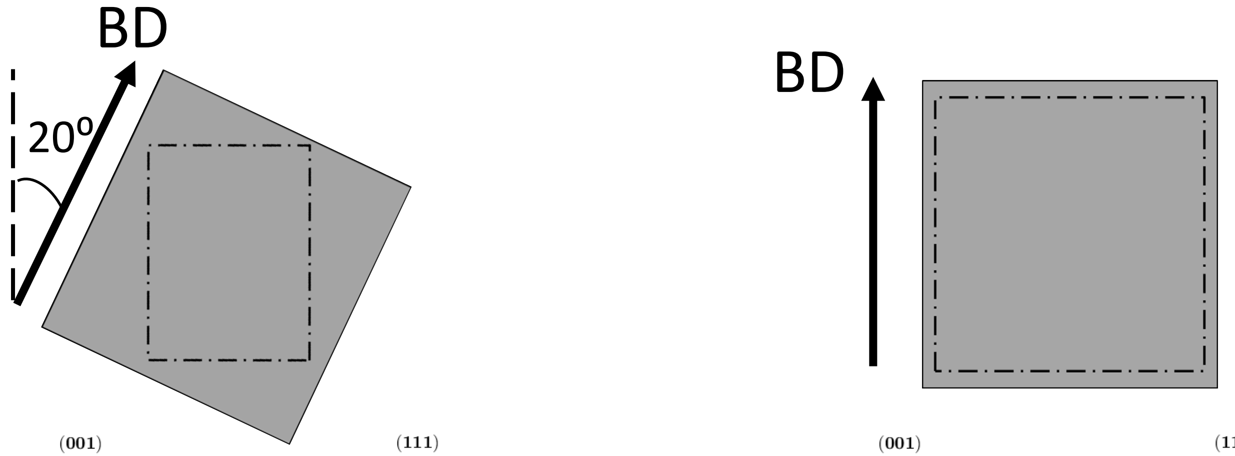

111
001
101


4mm

Neutron diffraction pole figures agree with EBSD pole figures

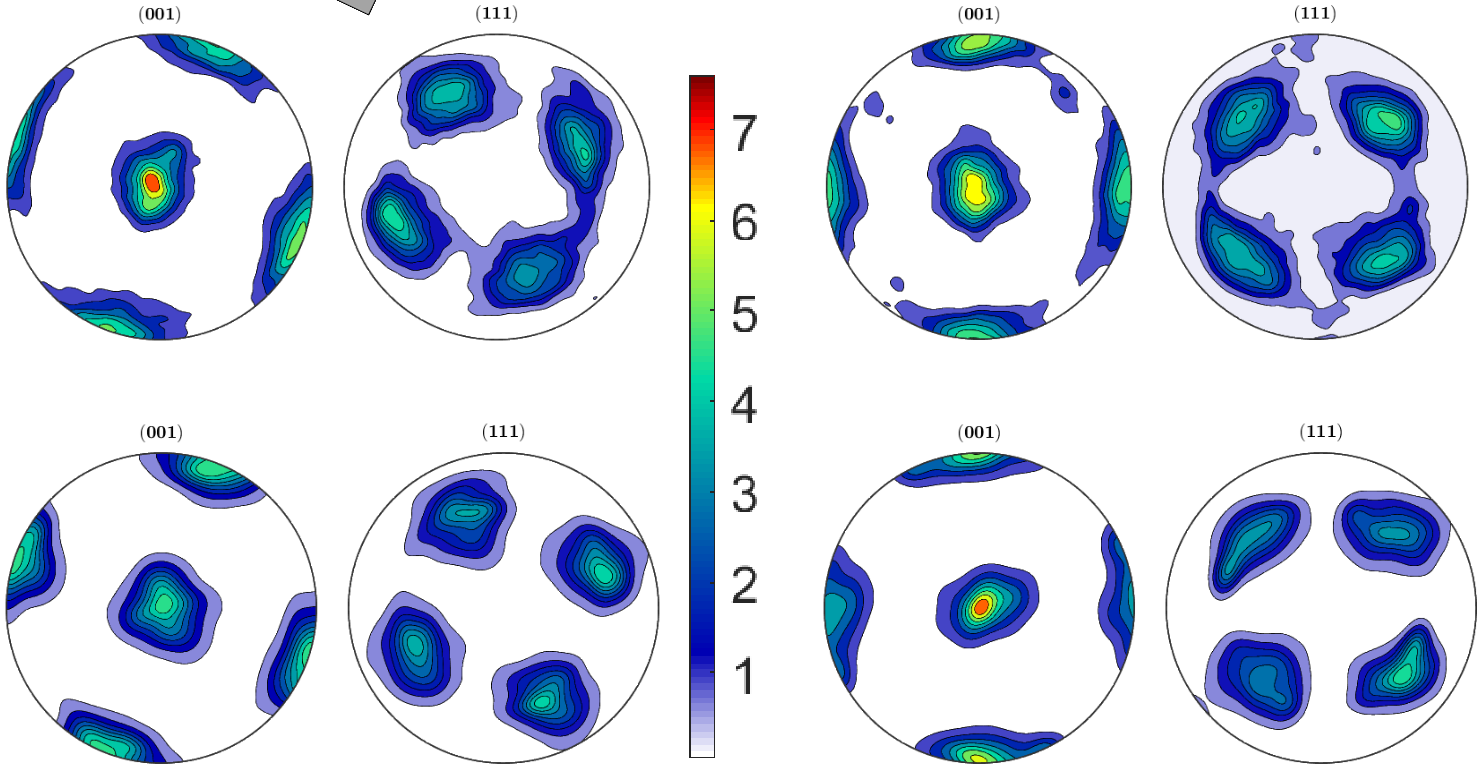






EBSD

Neutron



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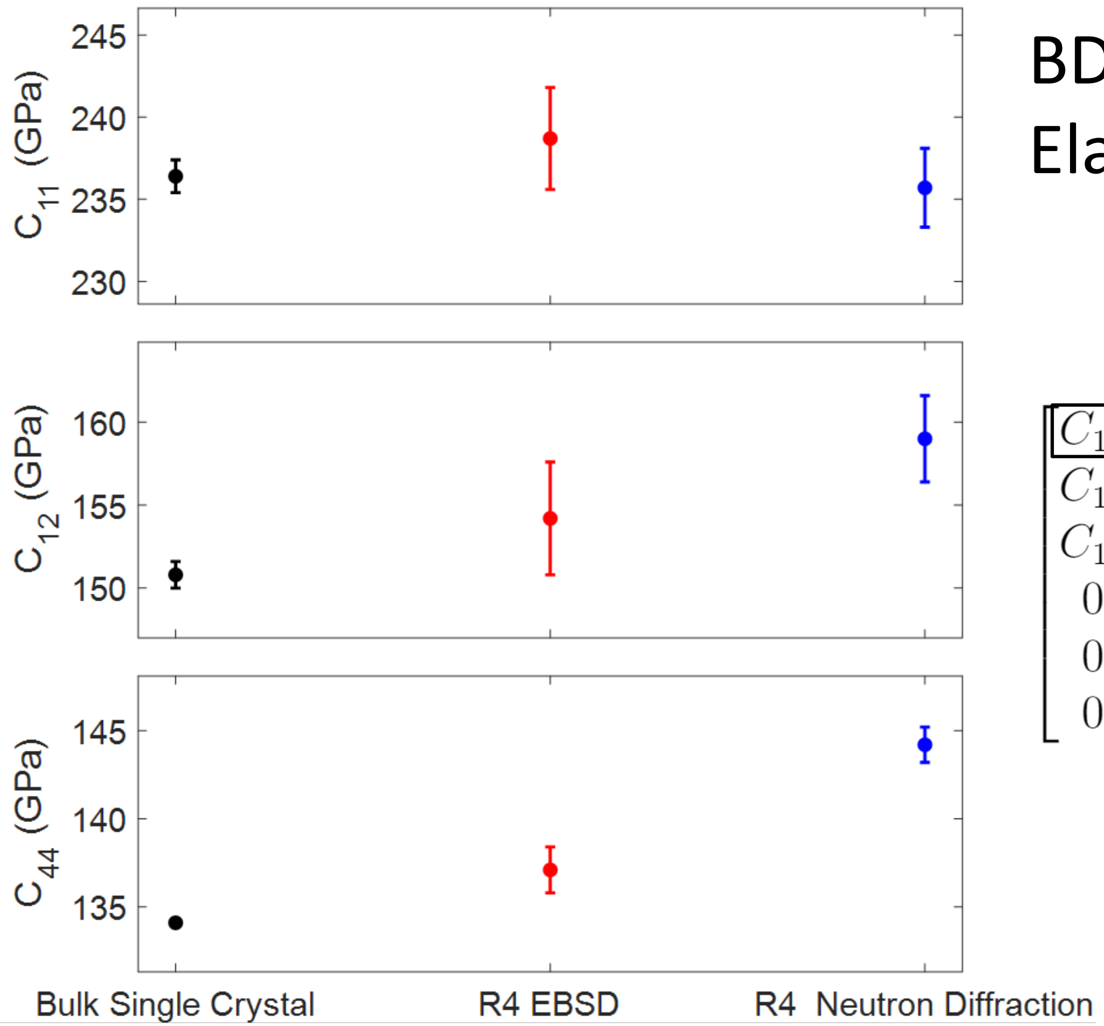
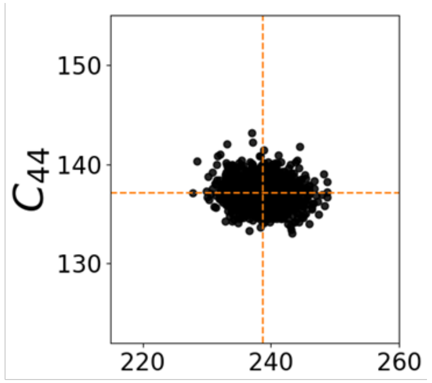
BD-aligned specimen: Elastic constants

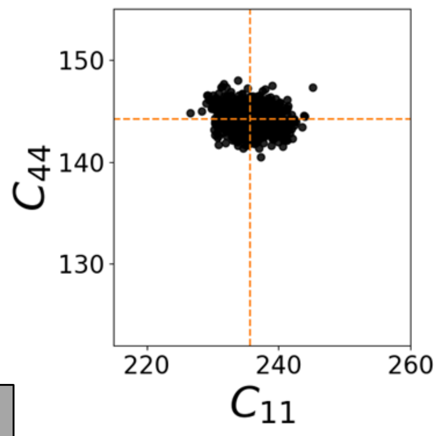


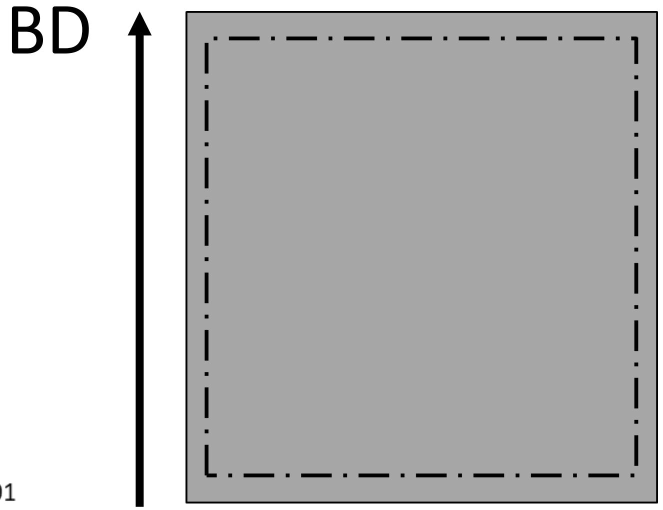
EBSD

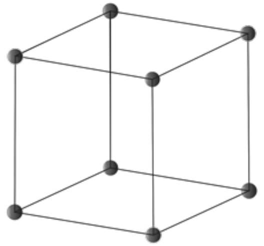


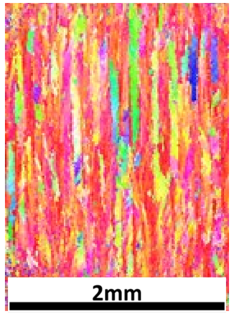
$$\begin{bmatrix} \boxed{C_{11}} & \boxed{C_{12}} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \boxed{C_{44}} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix}$$

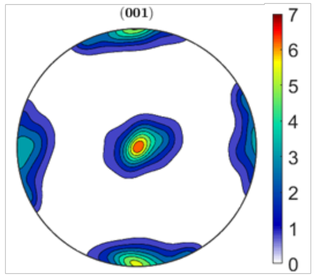
Neutron

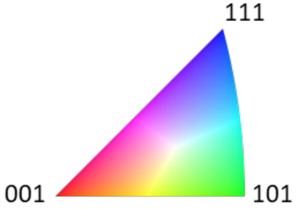




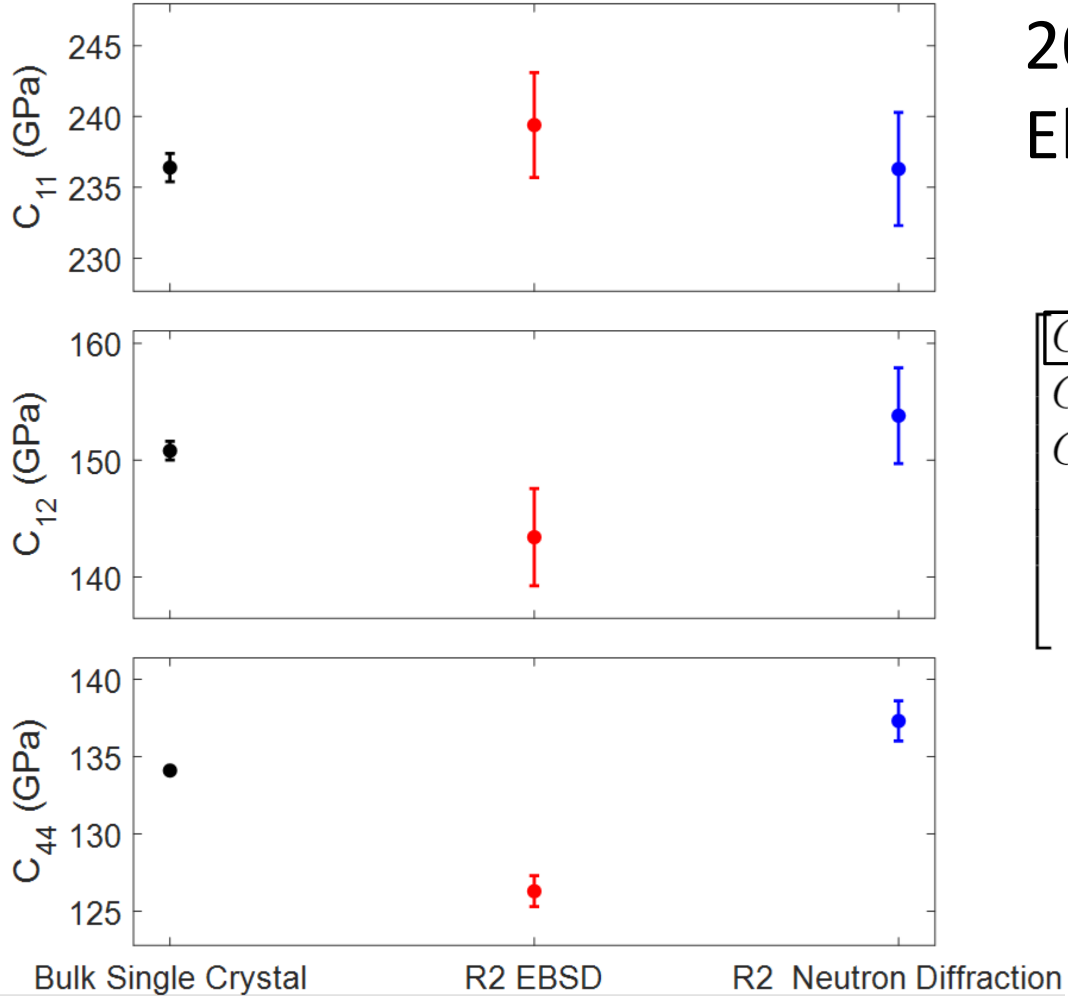




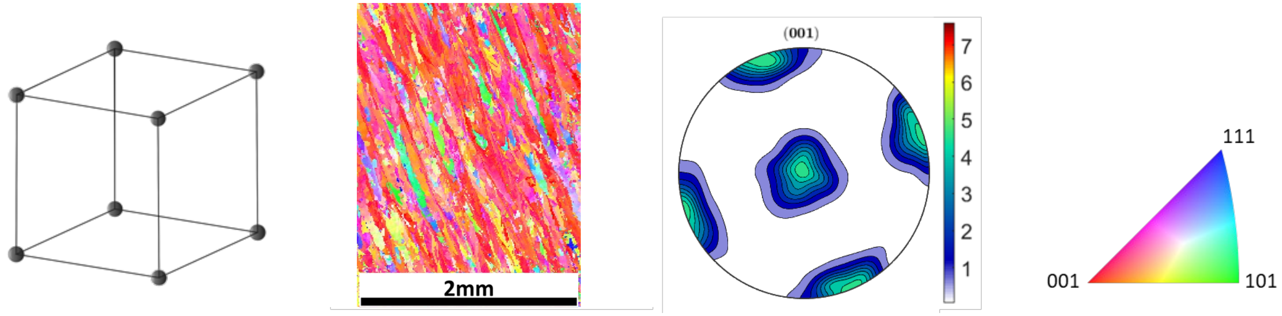


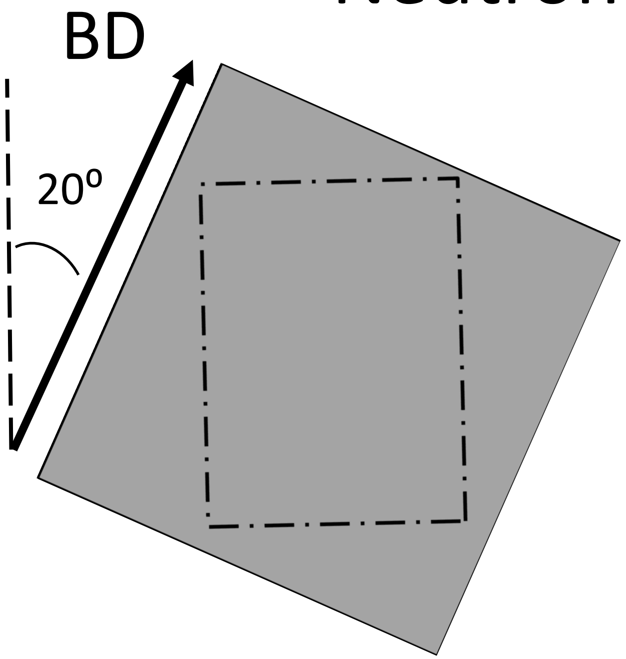


20°-aligned specimen: Elastic constants



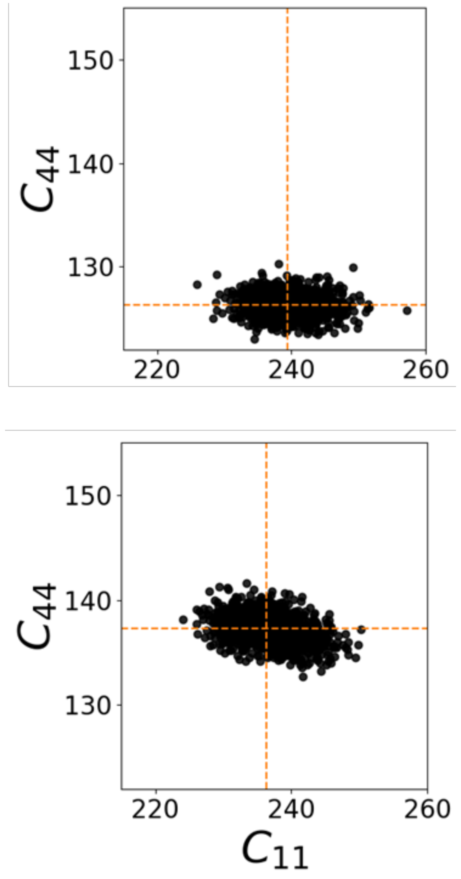
$$\begin{bmatrix} \boxed{C_{11}} & \boxed{C_{12}} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \boxed{C_{44}} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix}$$



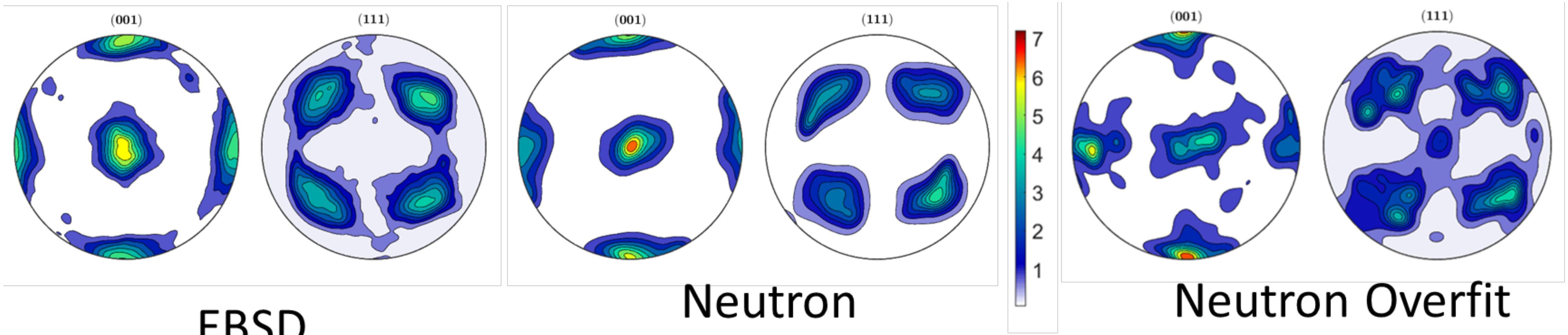


EBSD

Neutron



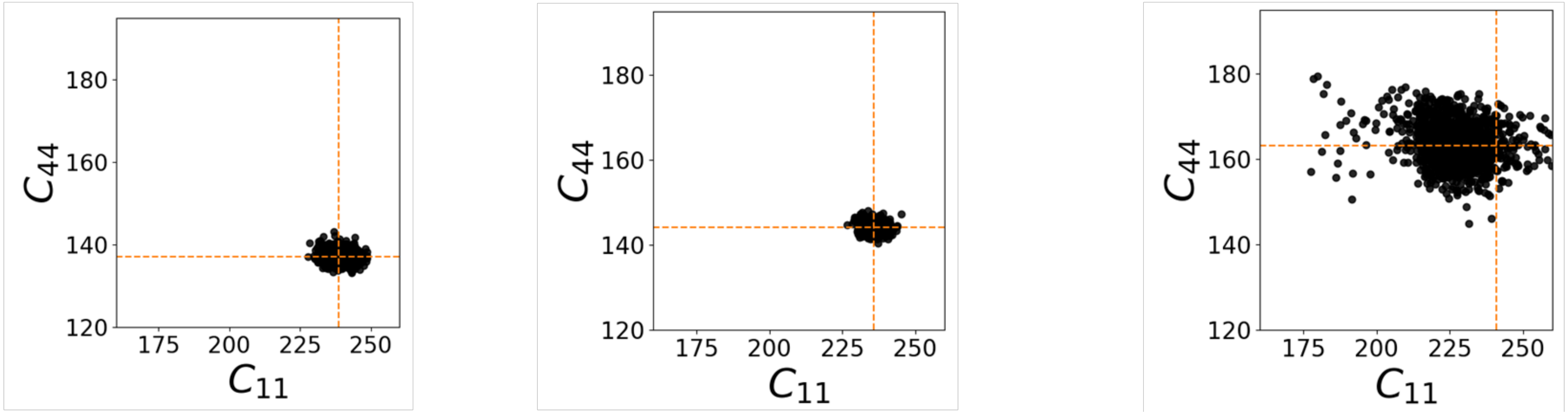
Error in data analysis affects single crystal estimate more than using EBSD



EBSD

Neutron
(R = 4.9%)

Neutron Overfit
(R = 8.8%)



238.7 ± 3.1 GPa

235.7 ± 2.4 GPa

241.0 ± 35.2 GPa

Summary

The resonance frequencies of AM samples can be gathered in <5 minutes

Determine the single crystal elastic constants

- EBSD data produces estimates comparable to those of neutron diffraction-informed estimates

Prerequisites

- Parallelepiped geometry
- Homogeneous texture through the bulk
- Anisotropy in the aggregate elastic properties
- Residual stresses removed from specimens

$$\left\{ \begin{bmatrix} f_1^{meas} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ f_n^{meas} \end{bmatrix} \right\}$$